Automation Middleware and Algorithms for Robotic Underwater Sensor Networks

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LONG-TERM GOALS

The long term goals of the project are: (1) To establish systems and algorithms for controlled Lagrangian particle tracking that will be used to improve the accuracy of model based prediction of trajectories of controlled underwater vehicles subjected to ocean current. (2) To achieve a mission planning system for robotic underwater sensor networks that are able to perform automatic or semi-automatic adaptation to extreme ocean conditions and platform failure, deployment, and recovery.

OBJECTIVES

We develop a set of automation middleware that implement a set of novel algorithms for robotic underwater sensor networks serving applications of ocean sampling and ocean model improvement. We design novel model adjustment, cooperative control, and distributed sensing algorithms that will be implemented through the automation middleware. The technical objectives include the following:

1. To investigate a new data assimulation procedure---the controlled Lagrangian particle tracking (CLPT)---and its ability to provide feedback adjustments on ocean modelling systems. To design a validation and adjustment algorithm for ocean models based on CLPT.

2. To develop an automatic middleware that integrates ocean models, robot models, and vehicle control systems towards more accurate prediction of the controlled trajectories of robots in the ocean.

3. To investigate cooperative filters and their ability to improve data quality collected by robotic underwater sensor networks.

4. To design automatic mission planning algorithms for missions with multiple objectives and multiple resolutions. To design a set of efficient and effective control and navigation algorithms that utilize ocean flow to increase mobility with guaranteed sampling performance.

5. To develop a mission planning and optimization system that automatically generates control laws and mission definitions based on user input about mission goals and constraints.

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APPROACH

The work is performed by PI Fumin Zhang and three graduate students: Justin Shapiro who entered Georgia Tech in fall 2008, Wencen Wu who entered Georgia Tech in Spring 2009, and Clementyna Szwaykowska who entered Georgia Tech on a NSF graduate fellowship in Fall 2007. In addition, three undergraduate students are hired on an hourly base to develop an experimental underwater vehicle. The PI is leading the team. Justin Shapiro focuses on system development and also leads the undergraduate students to develop test-bed that includes underwater vehicles. Wencen Wu focuses on cooperative filtering and autonomy algorithms. Clementyna Szwaykowska focuses on the CLPT theory and model reanalysis.

The approach and methodologies employed, corresponding to the above objectives, are as follows:

1. We define the CLPT error as the difference between the predicted trajectories of the robots through simulations using ocean predictions and the actual trajectories of the robots through real ocean experiments. This error is averaged across all robots in a network to generate the average CLPT error. The Eulerian flow predictions generated by ocean models can be improved by minimizing the average CLPT error.

2. We develop a middleware system for CLPT to establish an automatic connection between the ocean modeling systems (NCOM, ROMS, HOPS) and the underwater robot control systems (GCCS or an AUV control system such as the MOOS).

3. We develop cooperative filters that provide optimal least square interpolation for ocean data collected along the trajectories of the robots. A rigorous mathematical approach is followed to justfiy the theoretical soundness of the method. A cooperative Kalman filter is developed as an extension to the original Kalman filtering algorthm (Jazwinski 1970; Stengel 1994). We apply the cooperative Kalman filter algorithm to estimate the representation error for data assimilation in three dimensional space. Error associated with such estimation can be minimized by optimizing the shape of the robot cluster and the time step of the estimation.

4. We use the technique of multiple objective optimization (Sawaragi, Nakayama et al. 1985; Boyd and Vandenberghe 2002) to produce optimal mission designs that satisfy multiple objectives under the constraints for structure and adaptiveness. We address the combination of two sampling problems: feature tracking and coverage control. In both problems, the trajectories with maximum efficiency will be computed based on optimal control techniques.

5. We develop a middleware system named the automatic mission planning and optimization (AMPO) system that establishes an automatic connection between the users and the underwater robot control systems. We develop a testbed that including ROVs and AUVs to test this system.

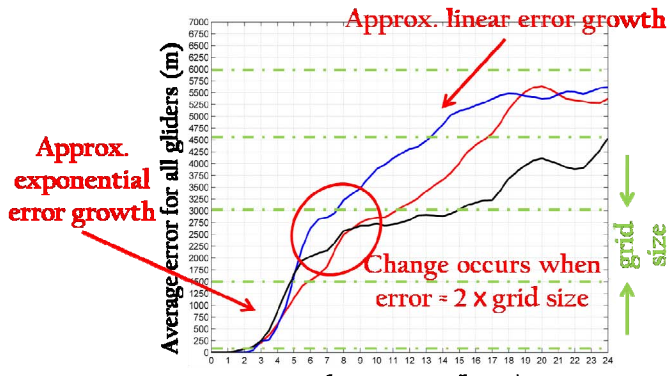

Figure 1. Similar behaviors of the averaged CLPT error across all three ocean models

WORK COMPLETED

Averaged CLPT errors have been computed for ROMS, NCOM, and HOPS ocean models by comparing glider trajectories in the 2006 ASAP experiment in Monterey Bay, CA with recently regenerated ocean predictions. This process is named as model reanalysis. Model reanalysis reports have been generated for different versions of both the NCOM and the ROMS models. Such reports allow the modeling teams to test hypothesis made towards improving ocean models, as shown in Figure 1. A rigorous analysis based on the stochastic systems theory has been used to explain the common trend shared by the CLPT error plot of all three models. We have rigorously proved that there exists a lower bound on the steady state CLPT error. Such lower bound is determined by the grid size of ocean models. Therefore, increasing the spatial resolutions of ocean models will effectively reduce the CLPT error. Our results have been published as a conference paper (Szwaykowska and Zhang 2010) with its journal version in preparation.

The cooperative Kalman filtering method has been developed for two dimensional ocean fields. Theoretical results show the method is provably convergent (Zhang and Leonard 2009) . A level curve tracking algorithm based on this method has been verified through simulation, see the left figure in Figure 2. We developed autonomy algorithms for mission planning that produces cooperative exploration behaviors under tidal current. See the right figure in Figure 2. Cooperative filtering and cooperative exploration algorithms have been extended to track small features in a three-dimensional field as shown in Figure 3. The number of vehicles have to increase comparing to the two dimensional case, the minimum number of vehicles required have been determined theoretically (Wu and Zhang 2010).

Methods for evaluating performance of the middleware systems are developed under the framework of cyber-physical systems (Zhang et al 2008). Cyber-physical systems theory integrates the design of computer system and physical systems to achieve optimal overall performance. Work has been completed on predicting the performance of glider autonomy under long communication delays and asynchronicity.

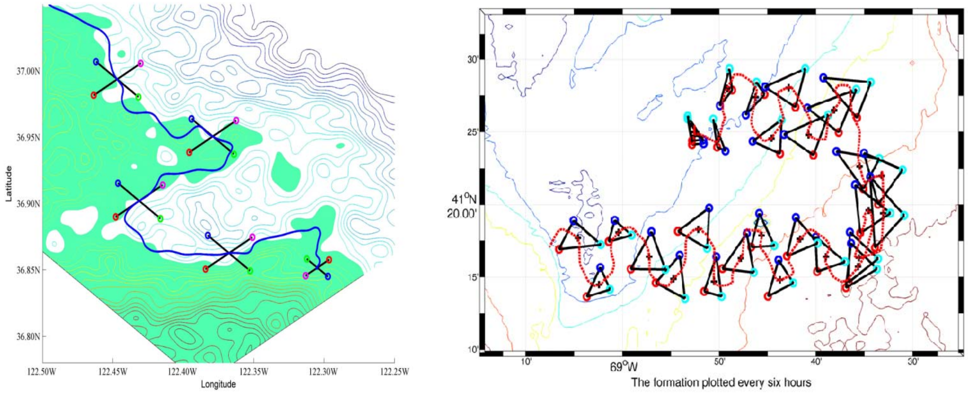

Figure 2. Cooperative exploration behaviors. Snapshots of the robot formation are plotted along the trajectory of the center of the formation. Left: tracking a temperature level curve using four robots. Right: autonomous mission planning under tidal current.

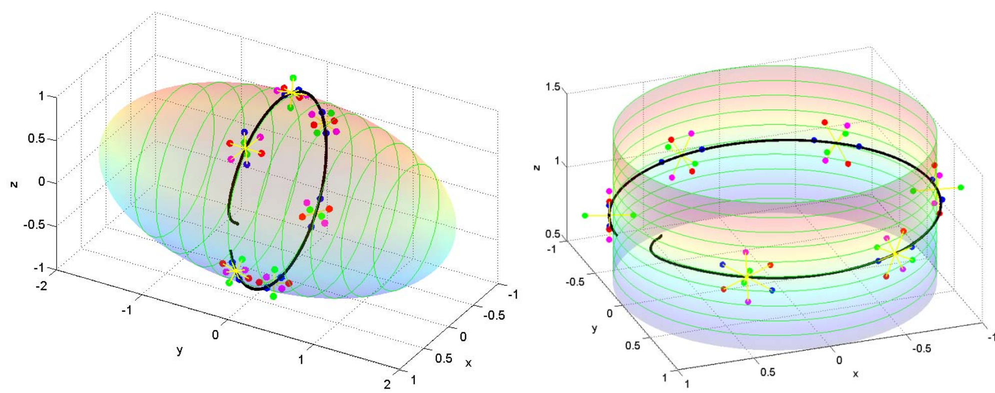

Figure 3. Demonstrations of three dimensional cooperative exploration algorithms.

We have developed a remotely operative vehicle (ROV) that has won a design exellence award in the 2009 MATE international ROV competition, as shown in Figure 4a. A more advanced ROV is developed for the 2010 MATE international ROV competition with capability of underwater manipulation, as shown in Figure 4b.

RESULTS

1. We noticed similar behaviors for all three ocean models regarding the averaged CLPT error in Figure 1. The error first grows exponentially until it reaches twice the grid size. After that, the error grows linearly. Using stochastic systems theory, we are able to explain this similarity. We made the discovery that this behavior is unique to controlled Lagrangian particles i.e. robots. We believe this cannot be observed on drifters. Further test and analysis on experimental data are planned to confirm this conjecture.

2. Cooperative filtering and exploration behavior are fundamental building blocks for autonomy of networked unmanned marine systems. Our theoratical developments show that cooperative filtering can be used to explore both 2D and 3D scalar fields.

3. Cyber-physical systems theory has the potential to optimize both the performance of the mission control and the computing systems for robotic underwater sensor networks. A dynamic battery model is developed to enable energy efficient mission planning.

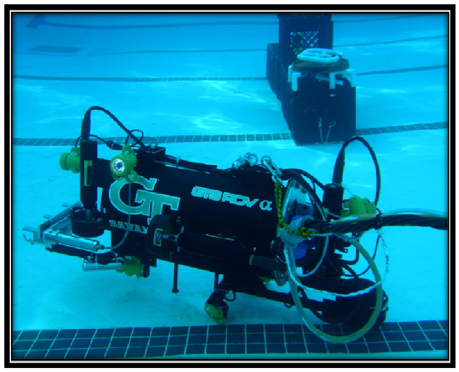

Figure 3a. The GTS ROV alpha in the 2009 MATE international ROV competition

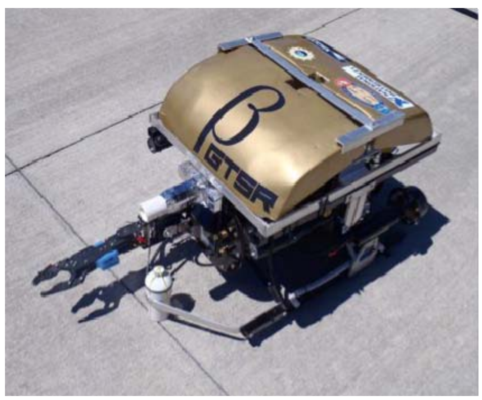

Figure 3b. The GTS ROV beta in the 2010 MATE international ROV competition

IMPACT/APPLICATIONS

The infrastructure we are developing will lead to the fully automated operation of underwater robotic sensor networks that are persistent and intelligent in a constantly changing ocean environment. On top of the operation automation that results in autonomy, the data flow in and out of the autonomy is automated. This impacts not only the gathering of data, but also the assimilation of the gathered data and the improvements of ocean models.

RELATED PROJECTS

The middleware and algorithms are connected with other important research activities of the PI and others around the theme of adaptive sampling using underwater robotic sensor networks.

1. Ocean modeling and glider data assimilation. The middleware design goes hand in hand with the work of the ocean modeling teams from NRL Stennis and NASA JPL. The middleware systems will provide automatic validation and adjustment methods to reduce the CLPT error to improve the accuracy of ocean flow prediction and may be applied to other state variables of the models. Algorithms in estimating the representation error will improve the accuracy of data assimilation.

2. Bio-Inspired Autonomous Control for Optimal Exploration and Exploitation in Marine Environments (BioEx). PI participated in this project sponsored by the ONR. The project goal is to institute an innovative multidisciplinary investigation of autonomous collective foraging in a complex environment that explicitly integrates models and insights from biology with models and provable strategies from control theory. Our methods for autonomy will be rigorously developed and tightly integrated with experimentation

3. Collaborative interface design. Middleware development will benefit from the continuing effort to improve MBARI COOP and other collaboration tools. On the other hand, the functionality of automatic mission and controller design will shorten the time from when a decision is made to when the decision is implemented.

4. Ocean science missions. The Middleware systems developed will be used to two recent ocean science missions the PI participates. One mission will deploy underwater gliders in Long Bay, SC to study mechanisms of nutrient input at the shelf margin supporting persistent winter phytoplankton blooms downstream of the Charleston Bump. The other mission uses the robotic platforms the PI developed to survey estuarine area near Louisiana Coast for trace of oil spill.

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PUBLICATIONS

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Szwaykowska, K. and F. Zhang (2010). A Lower Bound for Controlled Lagrangian Particle Tracking Error. *Proc. 49th IEEE Conference on Decision and Control* (CDC 2010). [accepted, refereed]

HONORS/AWARDS/PRIZES

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: 2009 NSF CAREER Award
Sponsor: National Science Foundation

Recipient: Georgia Tech Savannah ROV team (Led by Fumin Zhang and Justin Shapiro)
Institution: Georgia Institute of Technology
Award: Design elegance award of the 2009 MATE international ROV competition
Sponsor: Marine Advanced Technology Education (MATE) Center

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: 2010 ONR YIP Award
Sponsor: Office of Naval Research

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: 2010 Lockheed Inspirational Young Faculty Award
Sponsor: Lockheed Martin Co.